POI

Manuscript title:

Assessment of aerobic capacity and walking economy of unilateral transfemoral amputees

Abstract

Background; Studies of the maximal oxygen uptake (VO_{2max}) of transfemoral amputees (TFA) have mostly used protocols that activate a relatively small muscle mass. Consequently, TFA VO_{2max} may be systematically underestimated, and the validity of these test protocols is questionable.

Objectives; 1) Investigate validity and reliability of a VO_{2max} walking protocol. 2) Compare the VO_{2max} of a TFA group to a group of matching controls (CON).

Study design; 1) Randomized crossover study; walking vs. running VO_{2max} for the CON group, 2) case-control study; TFA vs. CON group $VO_{2max.}$

Methods; Twelve TFA and CON participants performed a walking VO_{2max} test with increasing treadmill inclinations to voluntary exhaustion. The CON group also completed a running ("gold-standard") VO_{2max} test.

Results; Mean (SD) CON group VO_{2max} following walking and running was similar, i.e. 2.99 (0.6) and 3.09 (0.7) $L·min^{-1}$, respectively. Mean (SD) TFA walking VO_{2max} was 2.14 (0.8) $L·min^{-1}$ (compared to CON; $p < 0.01$). Mean intra-class correlation coefficient (ICC) of repeated VO_2 measurements was 0.97, and within-subjects standard deviation (Sw) was 60 mL min^{-1}.

Conclusions; The walk protocol is valid. Walking VO_{2max} of TFA was 40 % lower compared to CON. Reliability of the walking protocol is comparable to other walking protocols.

Word count: 200

Clinical relevance

The design, alignment and materials of prostheses are important for effective ambulation. Cardio-respiratory fitness is, however, also important in this regard, and a low fitness may compromise health and independent living. Hence, TFA with low physical fitness should engage in regular physical activity to improve health, gait capacity and independency.

Word count: 50

Background

In clinical situations, an incremental exercise test of the maximal oxygen uptake (VO_{2max}) can be instrumental in identifying specific limiting physiological factors and in assessing the progress of exercise rehabilitation programs. Considering the increasing rate of lower limb amputations[1], there are surprisingly few studies that actually have reported the VO_{2max} values of lower limb amputees.[e.g. 2, 3, 4, 5] Using mainly test protocols based on one-leg cycle ergometry or upper body ergometry, these studies collectively report very low VO_{2max} values compared to predicted values for healthy individuals of the same age and sex.[6] A low level of VO_{2max} for transfemoral amputees (TFA) may be caused by several factors: The VO_{2max} may be systematically underestimated due to the choice of test protocol, i.e. the protocol is not valid. Alternatively, these individuals are physically deconditioned and the measured VO_{2max} thus represents their “true” VO_{2max}. Relating to the validity of VO_{2max} protocols, upper body ergometry and one-leg cycle ergometry activate much muscle mass than whole body exercise and using these test modes, healthy individuals generally achieves only 70 - 80 % of whole body VO_{2max}[7]. Consequently, upper body/one-leg cycling protocols are not ideal if measurements of whole body aerobic capacity is of interest. This emphasizes the need for a VO_{2max} protocol that activates a larger amount of muscle mass than protocols previously used by TFA, and in this regard, t*wo-leg* cycle ergometry may be an alternative. In a pilot study conducted in our laboratory, the VO_{2max} of TFA subjects following two-leg ergometer cycling was nonetheless 7 % lower compared to treadmill walking VO_{2max} ($p < 0.05$). Thus, treadmill walking may be an attractive alternative for VO_{2max} testing of transfemoral amputees. To be confident that a VO_{2max} test of TFA subjects actually is maximal, and that the results are valid, one should ideally perform a running VO_{2max} test and compare running VO_{2max} results to the walking protocol. Since most TFA are unable to perform a running test, this is, however, not an option.

Hence, the validity of a new VO_{2max} walk protocol was investigated by a group able-bodied healthy adults (CON) that was tested with a treadmill walking protocol to voluntary exhaustion and with a treadmill running protocol (i.e. a “gold standard” VO_{2max} test). If the walking protocol and the running protocol result in similar VO_{2max} values in able-bodied subjects, and objective criteria for achieving VO_{2max} are satisfied[8], one may assume that the incremental walking test is a valid test protocol for measuring VO_{2max}. Given this, the walking protocol will unquestionably generate sufficient physiological stress to generate VO_{2max} in transfemoral amputees. Hence, the measured VO_{2max}

following the present treadmill walk protocol will likely represent the “true” VO_{2max} of the transfemoral amputees. Since the validity of an exercise test also is dependent on its reliability, the reliability of the treadmill walk protocol was examined by repeating the walk protocol three times and comparing VO_2 responses at the different treadmill inclinations of the protocol. Accordingly, the main hypotheses of the present study were:

1) There is no difference in the mean VO_{2max} of able bodied subjects (CON) following an incremental walking protocol compared to mean VO_{2max} values following a “gold-standard” running protocol.

2) Walking protocol mean VO_{2max} of trans-femoral amputees (TFA) is lower compared to VO_{2max} of able-bodied subjects (CON) with matching age, height, weight, sex and self-reported physical fitness.

3) The Intraclass Correlation Coefficient (ICC) of repeated walk protocol VO_2 measurements is better than 0.90.

Keywords: Energy expenditure; Gait; Preferred Walking Speed; VO_{2max}

Methods

Participants

Three groups of participants were recruited to participate in the present study. Groups TFA and CON participated in a test to investigate the validity of a treadmill walking protocol for measuring the VO_{2max} of transfemoral amputees, while the third group (group REL) participated in a test to examine the reliability of the treadmill walk protocol. Participants of the TFA group were non-smoking adults (six females and six males) with unilateral transfemoral amputation for at least two years for reasons other than vascular diseases, and in general good health. All participants in this group used their prosthesis on a daily basis and were able to walk continuously for at least 500 m with no or only moderate support from a cane or an elbow crutch. Eight of the TFA subjects used a microprocessor controlled knee-joint, while four subjects used other advanced mechanical knee-joints. The participants in the control (CON) group were matched for weight, height, age, sex and self-reported physical fitness. The CON subjects were healthy, non-smoking adults (six females and six males) with no orthopedic problems. The participants in the reliability (REL) group were healthy, non-smoking adults (five females and five males). Self-reported physical fitness (SPF) of all participants was evaluated by a five-point Lickert scale (1 = very good, 3 = average, 5 = very poor). Details of the physical characteristics of the TFA, CON and REL group is shown in Table 1. All participants were instructed to avoid large meals and coffee for a minimum of three hours before testing and to avoid exercise and alcohol 24 hours before testing. Written informed consent was obtained from all subjects. This study was approved by the XXXXXX XXXXXXXXX XXX XXXXXX XXXXX XX XXXXX.

Measurements

Oxygen uptake (VO_2), lung ventilation (VE) and respiratory exchange ratio (RER) were measured by a stationary ergo spirometer (Sensor Medics Vmax229, CA, USA). Heart rate (HR) was monitored by a Polar heart rate monitor (Polar Electro, Kempele, Finland). For all test protocols, a calibrated Woodway ELG70 motorized treadmill (Woodway, Weil am Rhein, Germany) was used. Walking economy (C_w; $mL \cdot kg^{-1} \cdot meter^{-1}$) during steady state conditions was calculated during flat treadmill walking by dividing the participants VO_2 values by their respective preferred walking speed (PWS).

Criteria for VO_{2max}

The VO_2 measurements were considered maximal when the oxygen uptake did not increase > 2 $mL \cdot kg^{-1} \cdot min^{-1}$ (plateau in VO_2) in combination with RER values > 1.05, despite increased workload.[8]

VO_{2max} *walking protocol* (TFA and CON groups)

It is improbable to achieve VO_{2max} during ordinary walking on a flat treadmill. Thus, in order to induce sufficient physical stress to attain the participants' maximal aerobic capacity, we used a modified treadmill walking test[9] with progressively increasing inclinations. The walking protocol consisted of three sequences: Sequence 1 started with the determination of the participants' PWS on a flat treadmill.[10] When the PWS was decided, the participants continued directly to sequence 2, which was continuous walking at the PWS for a total of 10 minutes (warm-up). Following warm-up, the participants proceeded directly to the VO_{2max} test (sequence 3). During sequence 3, the walking speed was kept constant at the participants respective PWS, while the inclination on the treadmill was increased by 3.5 per cent every third minute until voluntary exhaustion. For every inclination, physiological measurements (VO_2, VE, HR) were averaged over the last 30 seconds of each three minute stage. If the participants were unable to complete three minutes of walking during their final stage, values were averaged over the last 30 seconds preceding exhaustion. Rating of perceived exertion (RPE; 0-10) was recorded at rest and immediately following termination of testing. The participants were allowed to have one hand resting lightly on the treadmill handrail to assist in keeping balance.

VO_{2max} running protocol (CON group)

The sequence of testing started with slow jogging (7-8 $km \cdot h^{-1}$) on a treadmill with zero inclination for 10 minutes. Following this warm-up sequence, the inclination of the treadmill was increased by 1.0 % every 60 seconds until the inclination was 5.2 % (same running speed as during warm-up). The inclination was then kept constant at 5.2 %, but the speed of the treadmill was increased with 1.0 $km \cdot h^{-1}$ every 60 second until voluntary exhaustion. Physiological measurements (VO_2, VE, HR) were averaged over the last 30 seconds of each 60 second interval.

Reliability of repeated walk tests (REL group)

To investigate the reliability of the treadmill protocol used by the TFA and CON groups, the participants in the REL group performed the walking protocol a total of three times with a recovery period of 3-7 days between each test. The participants' PWS was determined during test 1 as previously described and used throughout the study. The test procedure was similar to VO_{2max} walk protocol used by the TFA and CON group with the exception that sequence 3 were terminated when the REL subjects had completed 3 minutes of walking at 21.0 % inclination. Thus, the VO_2 values at this inclination do not necessarily represent the VO_{2max} of these subjects. For every inclination, physiological measurements (VO_2, VE, HR) were averaged over the last 30 seconds of each three minute period.

Step frequency and step length

PWS step frequencies during treadmill walking (zero inclination) was measured by manually counting the number of steps for two periods of 30 seconds each, and then taking the average of the two periods. The step length was calculated by dividing the walking distance by the step frequency.

Statistics

An equal variance (equivalence) test was performed to test for similarity of the running and walking VO_{2max} means of the CON group. Comparisons between the CON and TFA groups were done by independent samples *t*- test, and within-group comparisons with paired *t*-tests. Means of three repeated walk tests of the REL group was initially analyzed with one-way repeated measures ANOVA and the Sidak post-hoc test when appropriate. The relationship between PWS and VO_{2max} values was analyzed with Pearson's product moment correlation and outliers treated according to Chatterjee and Hadi[11], while the relationship between subjective ratings of fitness and preferred walking speed was analyzed with Spearman's rank correlation. In addition, intra-class correlation coefficient (ICC 1, k) was analyzed according to Shrout and Fleiss[12], while within-subjects standard deviation (S_w) was calculated according to Bland and Altman.[13] Agreement between VO_{2max} values obtained from the walking and the running protocol for the CON group was assessed according to Bland and Altman.[14] The significance level was set at $p < 0.05$. The data were analyzed by the SPSS version 18.0. Results are presented as means and standard deviations (SD).

Results

Insert table 1 about here

Physical characteristics of the participants (table 1)

For the participants of the TFA group there was an inverse relationship ($r = -0.75$, $p < 0.001$) between their self-reported fitness and their PWS ($m \cdot min^{-1}$), meaning that the slower preferred walking speeds (PWS) were associated with the poorer subjective ratings of fitness. Consistent with this, there was a positive relationship ($r = 0.85$, $p < 0.002$) between the TFA participants PWS ($m \cdot min^{-1}$) and their VO_{2max}, $L \cdot min^{-1}$ (Fig 1). In contrast, there were no relationships for the CON group regarding their VO_{2max}, PWS or self-reported fitness.

Insert figure 1 about here

Time-distance parameters, oxygen uptake and walking economy during treadmill walking at the subjects PWS (table 2).

There were significant differences in PWS, step frequency and step length of the TFA group compared to the CON group (all comparisons, $p < 0.001$). The relative oxygen uptake for the TFA and the CON group was similar, but the TFA group used a much larger mean (SD) percentage of their VO_{2max} during PWS walking compared to the CON group (i.e. 47 (9) and 35 (3) % of VO_{2max}, respectively ($p < 0.001$). Walking economy (C_w) for the TFA group was significantly higher than for the CON group ($p < 0.001$), but this is mainly the result of the slower PWS of the TFA group.

Insert table 2 about here

VO_{2max} following the running and walking tests (table 3)

Following the treadmill walking protocol, the VO_{2max} of the TFA group was about 30 % lower compared to the healthy controls (i.e. 27.1 vs. 38.7 $mL \cdot kg^{-1} \cdot min^{-1}$), $p < 0.01$. For the CON group, there were no significant differences in VO_{2max}, VE_{max}, HR_{max}, RER_{max} or RPE_{max} values when comparing the running and walking tests.

Insert table 3 about here

Insert figure 2 about here

To assess the relation between the VO_{2max} values obtained by the running and walking protocol for the CON group, a Bland-Altman plot was constructed (Fig. 2). The mean difference between walking and running VO_{2max} was -1.18 $mL \cdot kg^{-1} \cdot min^{-1}$, with upper and lower limits of agreements of 3.6 and -5.9 $mL \cdot kg^{-1} \cdot min^{-1}$.

Physiological parameters at VO_{2max}

The mean (SD) time to VO_{2max} (excluding warm-up) during the walk test for the TFA group was 16.3 (2.9) minutes. The mean (SD) time to VO_{2max} of the CON group was 16.8 (1.5) minutes and not different from the TFA group. Mean heart rate at VO_{2max} (HR_{max}) of the TFA group was similar to the mean (SD) age-predicted HR_{max} of 177 (14). HR_{max} for the CON group during walking and running was similar to the mean (SD) age-predicted HR_{max} of 177 (12) $beats \cdot min^{-1}$. Following the running protocol, the speed at VO_{2max} for the CON subjects varied between 9 and 13 $km \cdot h^{-1}$, with a mean (SD) speed of 11 (1.5) $km \cdot h^{-1}$.

Criteria for VO_{2max}

For the TFA subjects, two subjects did not experience a plateau in the oxygen uptake at the time of exhaustion. If no plateau is reached, secondary parameters may assist in determining if the test was maximal. That is, if RER is greater than 1.05 in combination with HRmax values close to or equal to the age-predicted HRmax, the test is probably maximal. The RER values at the time of exhaustion (RER_{max}) of the two participants without a plateau in the oxygen uptake were > 1.06, and the HR_{max} during testing was within 2-4 beats of their age predicted HR_{max}. For the CON subjects, three subjects did not experience a plateau in oxygen uptake during either test protocol. RER_{max} for these participants were > 1.06 during walking, while running RER_{max} was > 1.11, and also for these subjects, the measured HR_{max} during testing was within 2-4 beats of their age predicted HR_{max}. Collectively, based on respective RPE scores, RER and HR values, the test were judged maximal also for the subjects without a plateau in oxygen uptake values.

Reliability of repeated treadmill tests (table 4)

The intra-class correlation (ICC) for the VO_2 measurements were generally very high (mean; 0.97) over the whole range of treadmill inclinations (Table 3). The within subjects standard deviation (S_w) can be considered a measure of absolute reliability (method error), and in the present study the S_w of the VO_2 measurements varied between 40 and 90 (mean 60) $mL \cdot min^{-1}$.

Insert table 4 about here

Discussion

Validity of the walking protocol

In the present study, a group of healthy adults (CON) with average self-reported fitness were tested on a treadmill with a VO_{2max} walk protocol used by transfemoral amputees[15] and with a VO_{2max} running test ("gold standard" test). The VO_{2max} values of the CON group were similar 'following the walking and the running protocol (~40 mL kg^{-1} min^{-1}), demonstrating that the CON subjects achieved similar individual VO_{2max} by both protocols. To judge the level of agreement between the "gold-standard" VO_{2max} test and the VO_{2max} of the walk test, a Bland-Altman plot was constructed (Fig. 2).

All individual data points are relatively well collected and within the upper and lower control limits. In addition, the mean difference between the two tests was about -1.2 ml kg^{-1} min^{-1}, and this small difference is within acceptable limits. In addition, judging by each subjects work rate – VO_2 relationship (plateau in VO_2 measurements despite increases in work rate) and RER values at voluntary exhaustion, objective criterions for having achieved VO_{2max}[8] seems to be satisfied. In sum, the walk test is a valid test of VO_{2max} for moderately fit subjects. The average VO_{2max} of the TFA (~27 mL·kg^{-1}·min^{-1}) in the present study was higher than reported in earlier studies,[2,3,4,5,16] but still these values are only about 70 % of the CON group VO_{2max}. Hence, the TFA participants have considerably lower cardio-respiratory fitness than able-bodied subjects with similar age, height, weight, sex and self-reported fitness. In this regard, it is argued that only those amputees who have adequate fitness will become successful prosthetic users[4]. Consequently, TFA should engage in regular physical activity to reduce the risk of further reductions of their cardio-respiratory fitness and to ensure effective prosthetic ambulation.

To put the VO_{2max} values of our TFA and CON subjects into a larger perspective, the walking CON and TFA VO_{2max} were compared to walk-protocol VO_{2max} data obtained from a large sample of XXXXXXXXX healthy men and women of different ages.[8] In this context, we find that the CON VO_{2max} (~40 ml kg^{-1} min^{-1}) is similar to the average VO_{2max} of healthy men and women with similar age as our participants (i.e. ~41 ml kg^{-1} min^{-1}). Thus, the VO_{2max} of the CON participants seems to be representative of healthy, moderately fit male and female XXXXXXXXX, and this strengthens the assumption that the low VO_{2max} values of the TFA using the treadmill walking protocol, is not the result of an inadequate test protocol, but represents the actual VO_{2max} of these subjects. Pitetti and Manske[17] have, however, raised concern that the combination of reduced walking economy (compared to able bodied persons) and the risk of painful skin breakdowns and following infections during prolonged walking preclude walking as a useful physical activity pattern during exercise and testing. As for skin breakdowns, may be a problem if the prosthesis is not well fitted to the amputee. In the present study, however, all participants had good skin quality and completed the walk test without problems of this kind.

Walking economy (C_w)

In the present study, the relative oxygen uptake during level treadmill walking with the PWS was similar for the TFA and CON group (12.2 and 13.4 $mL \cdot kg^{-1} \cdot min^{-1}$, respectively). On the other hand, the C_w was significantly higher (64 %) for the TFA group compared to the CON group (i.e. 0.24 vs. 0.16 $mL \cdot kg^{-1} \cdot meter^{-1}$). Most prosthetic users have, however, considerably slower PWS than healthy persons.[18] Since the calculation of walking economy is considerably influenced by walking speed, it may not be correct to judge the physical burden of prosthetic ambulation based on the C*w*, and especially not when the relative oxygen uptake is similar during PWS for able bodied persons and TFA persons.

It is, however, not uncommon in the literature to evaluate prosthetic gait based on calculations of the C*w*, [17, 18, 19] but it would probably be more informative to evaluate the energy expenditure of prosthetic walking relative to the amputees' *maximal* rate of oxygen uptake (VO_{2max}). When subjects were tested on a flat treadmill with their PWS, the TFA group in average utilized 47 % of their VO_{2max}, while the corresponding value for the CON group was significantly lower at 35 %. Thus, prosthetic ambulation is more strenuous than walking with two intact legs, not because of differences in walking economy, but because the TFA group uses a larger percentage of their total aerobic capacity than healthy individuals do. Hence, to judge correctly the physical burden of TFA gait, there is need of valid and reliable VO_{2max} protocols. Interestingly, there is a positive relationship between the PWS of the TFA participants and their respective VO_{2max} (Fig. 1), and to our knowledge, this is a novel finding for transfemoral amputees. Thus, while the prosthetic design, components and prosthetic alignment is important for effective ambulation, clearly also the cardio-respiratory fitness of transfemoral amputees may be important. In further studies it may be interesting to investigate whether improvements in aerobic capacity translates to improved walking speeds (and C*w*) in transfemoral amputees.

Reliability of VO_2 measurements

In order to investigate the reliability of the walk protocol, a group of healthy adults (REL group) performed the walking test a total of three times and the intraclass correlation coefficient (ICC) and within subjects standard deviation (S_w) was calculated.[12, 13] In the present study, the ICC scores were very high (Table 4) and better than reported for other comparable treadmill studies.[20] The ICC values in the present study were also considerably better than reported for repeated arm ergometry testing,[21] and also considering the low test-retest correlations for arm-ergometry,[22] it seems that walking protocols may be a preferable to other test modalities when considering test reliability. Probably, the high ICC scores are partly a result of a fairly homogenous test group, walking at a fixed speed, and that the test modality (walking) is a familiar type of movement. In addition, the measurement period was preceded by 10 minutes of habituation to treadmill walking, hence, variances in measurements due to learning effects are probably reduced.[23] The S_w, also called standard error of measurements (SEM) is commonly quoted as a measure of absolute reliability[24] and in the present study, S_w varied between 40 and 90 $mL \cdot min^{-1}$ (mean = 60 $mL \cdot min^{-1}$). For our participants, this corresponds to about 0.5 – 1.2 $mL \cdot kg^{-1} \cdot min^{-1}$. There are several studies that have examined test-retest reliability of treadmill walk protocols, and it is typically reported S_w values for VO_{2max} of 1.2 - 4.2 $mL \cdot kg^{-1} \cdot min^{-1}$.[20, 25, 26] Thus, the values of the present study are comparable or better than other studies, and we believe the observed deviations are well within tolerable limits.

Limitations of the study

One limitation of the present study may be that the VO_{2max} data is collected from a homogenous group of healthy transfemoral amputees with no cardiovascular or other diseases. Thus, one can expect that older TFA with circulatory or other diseases will have substantially lower VO_{2max} values than the TFA group in the present study. All TFA patients in the present study used advanced hydraulic or pneumatic knee components and they had little difficulties with treadmill walking. It remains, however, to be investigated how subjects with less sophisticated kne components will manage a treadmill-walking test with increasing inclinations.

Conclusion

In summary, we find that the VO_{2max} values obtained either by running or walking in the CON group is similar, and that repeated VO_2 measurements using the walk protocol show a high degree of accuracy. Thus, the walk protocol used in the present study is a valid and reliable test for measuring VO_{2max} of transfemoral amputees or healthy persons with average and less than average physical fitness. In addition, the VO_{2max} of the TFA group is substantially lower than the VO_{2max} of a matched control group, indicating that the TFA group in the present study is deconditioned. TFA should engage in regular physical activity, as improved fitness most probably would improve gait speed and ensure a more successful prosthetic ambulation.

Word count: 3500

Funding

This work was supported by a grant from the XXXXXXX XXXXX XXXXXXXXXX [grant number 23/09].

Conflict of interest

The authors declare that there is no conflict of interest

Acknowledgments

The authors thank the participants for their dedication and willingness to participate in this study

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